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A paper presented at the General Meeting of the American Institute of Electrical Engineers, New York, May 20th, 1896. President Duncan in the Chair.

EFFECT OF TEMPERATURE ON INSULATING MATERIALS.

BY GEO. F. SEVER, A. MONELL AND C. L. PERRY.

In designing electrical apparatus, it is often of the greatest importance to know the effect of different temperatures on the insulation to be used in its construction.

Of the many kinds of insulation, a few of the most common were chosen, *i. e.*, paper, cloth, oiled paper and oiled cloth, and the following conclusions have been drawn from the result of 102 tests on samples of materials, which were kindly furnished by several of the most prominent manufacturers of electrical machinery.

The Apparatus.

The heating apparatus consisted of a glass cylinder 8 inches in diameter and 10 inches high, covered at the top and bottom with asbestos plates. The lower part of this cylinder was occupied by twelve enamel resistance tubes, five inches long, and 24 ohms each. The terminals of these were brought out through the asbestos plate. The current in these tubes being controlled by a rheostat, the temperature in the cylinder could be varied at pleasure. An inch above the heating tubes, and supported by an asbestos collar, was a metal plate having holes punched in it to allow the free circulation of air in the cylinder. This plate was connected to one side of a galvanometer.

The insulating material to be tested was wrapped on brass cylinders $\frac{3}{4}''$ in diameter and three inches long, the insulation not reaching quite to the end of the tube. The insulation was then wound with No. 26 B & S bare copper wire for a

space of $2\frac{1}{2}''$. Five tubes so wound were then placed on the metal plate in the cylinder, and their terminals brought up through the asbestos cover, and then to a switchboard, in order that any tube might be thrown into the galvanometer circuit. This arrangement made it possible to heat five specimens at one time.

With the above apparatus was used a Thomson high resistance galvanometer, a megohm box and a difference of potential of 500 volts.

The thermometer used was of the nitrogen-filled mercurial type and capable of measuring from 0° to 400° C.

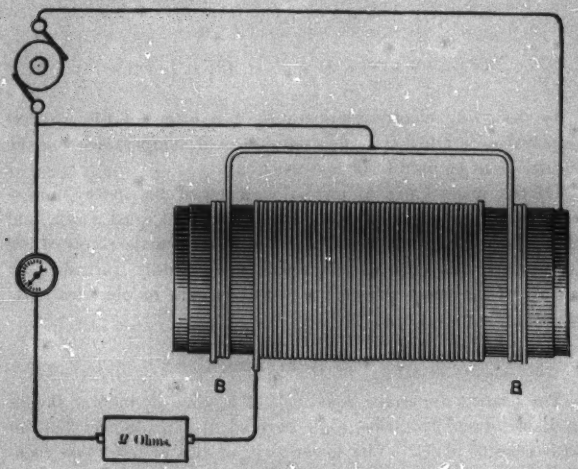

FIG. 1.

When troubled with surface leakage, it was eliminated in the following simple manner. The diagram shows the connections while testing a tube and also the leakage shunt.

It will be seen from the diagram, Fig. 1, that all of the current going through the galvanometer must pass from the dynamo to the brass cylinder, and thence through the insulation to coil A and on through the galvanometer. Any current tending to leak over the surface of the insulation from the brass cylinder to coil A will be intercepted and shunted past the galvanometer by coils B B.

During the investigation many different specimens of paper,

oiled cloth, etc., varying greatly in thickness and composition, were tested, and it was found that each class has its characteristic properties strongly marked. We will now proceed to the discussion of each particular class.

Plain Paper.

In this class 40 specimens were tested. After the resistance at the temperature of the air (22° C.) was carefully noted, the temperature was gradually increased (100° in one-half hour) and readings taken every 10° up to 80° and from there on every 20°. Fig. 2 shows a curve which is characteristic of practically all kinds of plain paper.

It should be noticed however that in general, the resistance of papers that are not protected from moisture, falls between 22° and 50° and then rises rapidly until at 75° it has attained a maxi-

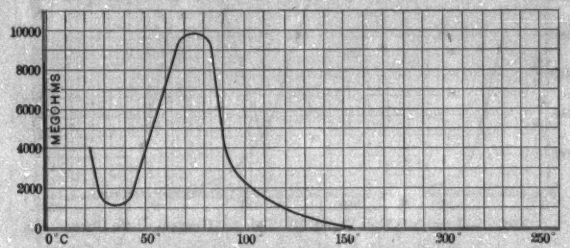

Fig. 2.—Plain Red Paper .009" Thick. Characteristic Paper Curve.

mum resistance. It should also be noted that this temperature of 75° is very constant for all kinds of paper. From 75° upward the resistance falls rapidly, and at 150° is but a small fraction of its initial resistance.

The initial resistance of paper protected from moisture by japan (Fig. 3) is very high, but falls rapidly with the increase of temperature, as is the case with all material protected from moisture. (See oiled paper and oiled cloth). Hence we see that all paper having a porous structure and therefore containing more moisture, has a lower initial resistance than the protected paper, but is affected by heat much less than the latter. This would lead to the conclusion that there are two phenomena taking place. First the driving off of the moisture, which tends to increase the resistance, and secondly, some change (not a mechanical deteriora-

tion) in the material, dependent on the temperature and which may be called the temperature coefficient. This temperature coefficient tends to lower the resistance with increase of temperature.

Examining the several curves shown, we see that the initial resistance of unprotected papers is low on account of the presence of moisture. Now, on gradually increasing the temperature, the resistance falls during the first 20° or 30°, because the effect of the temperature coefficient predominates during this period and before the material is warm enough to start the evaporation of the moisture it contains. This however lasts but a short time as the result of the evaporation is to increase the resistance very rapidly, until at 75° the temperature coefficient again asserts itself and the resistance rapidly falls.

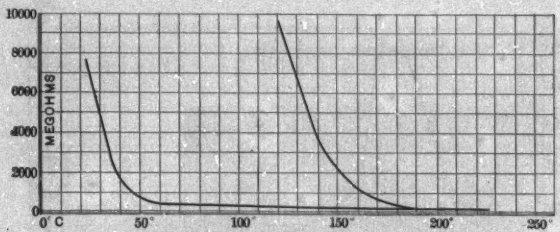

FIG. 3.—Japanned Red Paper .01" Thick. Characteristic Curve.

In the case of japanned papers (Fig. 3) the initial resistance is very high, due to the absence of moisture, but on being heated the resistance drops rapidly as the small quantity of water contained is evaporated off so slowly that it has very little counteracting effect on the temperature coefficient.

Paper does not seem to deteriorate mechanically at less than 180°; above this point the material begins to carbonize. At 230° a peculiar phenomenon takes place. The material after possessing a very low resistance from 175° upward, would at about 230° suddenly increase greatly in resistance and immediately after break down. This may be caused by some molecular rearrangement taking place at that temperature which changes the resistance of the material. Other cases wherein the resistance of a body changes at a certain temperature are well known. In the phenomenon of "recalescence" a piece of iron or steel after

having been heated to a bright redness and allowed to cool slowly will at a certain stage of the cooling process receive a sudden check, heat being generated in the metal as a result of the change which the molecular construction suffers at the critical point. The cooling is arrested and the temperature and resistance rise though the loss by radiation is still going on.

The experiments of F. Kohlrausch and Hopkinson have also shown that the critical temperature is marked by a sudden change in the coefficient which expresses the effect of temperature on the electrical resistance of iron. This is also true of nickel.

It would seem that paper insulation has a critical temperature somewhat analogous to that of iron, steel and nickel, but of course

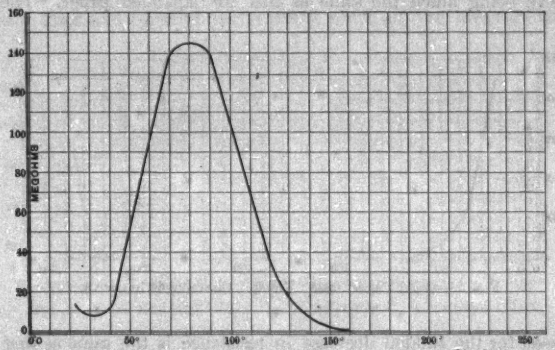

FIG. 4.—Plain Cotton Duck .015″ Thick. Characteristic Cloth Curve.

the characteristics of the materials are too different for any close similarity.

PLAIN CLOTH.

Under this head 20 specimens were tested including canvas, linen and muslin, of different thicknesses. The action of this material (Fig. 4) is much the same as that of paper (Fig. 2). The initial resistance is lower as it contains more moisture than is the case with paper; for the same reason when the moisture evaporates off, the increase over the initial resistance is greater than with paper. By reference to the curves of paper and cloth, it will be noticed that their resistance varies in the same manner. For cloth, as for paper, the maximum resistance is at 75 ° C. The

material does not begin to carbonize until at a temperature of 180° C. and even beyond that point it loses its mechanical strength very slowly until past 220°.

The explanation for the resistance of cloth varying as it does is exactly similar to that for paper.

Oiled Paper.

In this class 14 tests were made, on papers of different thicknesses. With the single exception of one specimen (the resistance of which was very high) the initial resistance was lower than in the case of paper. (Compare Figs. 2 and 5.)

On increasing the temperature the resistance fell rapidly, the curve being much the same as that for japanned paper. The

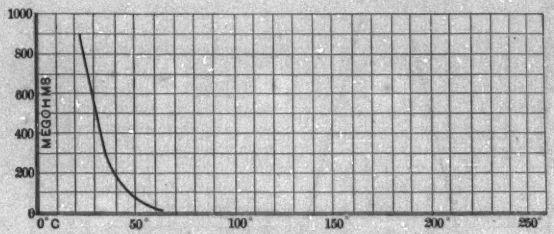

Fig. 5.—Oiled Paper .0045" Thick. Characteristic Curve.

reason for the sudden decrease in resistance is the same as that for japanned paper.

Oiled paper deteriorates mechanically at a lower temperature than paper or cloth, commencing to blacken at so low a temperature as 120° C.

Oiled Cloth.

In this class 28 specimens of oiled silk, muslin, and linen of various thicknesses were tested. The initial resistance of this material is much lower than that of paper, and on increasing the temperature the resistance falls rapidly, the shape of the curve (Fig. 6) corresponding to those of japanned and oiled paper. The reason for the sudden decrease in resistance is undoubtedly the same as for the japanned and oiled paper. The insulation begins to char at about 120° C.

General Conclusions.

In the foregoing discussion there are some main points to which it is necessary to draw attention. These are:

(*a*) That paper is a better insulation and withstands increase in temperature much better than cloth (shellac and varnish were not used in any of the experiments), oiled paper or oiled cloth.

(*b*) That paper and cloth have a maximum resistance when first heated at about 75° C. and are not injured mechanically under 180° C.

(*c*) That the point of maximum resistance for paper and cloth (in this case 75° C.) depends on the rapidity with which the temperature is increased.

Here the authors would like to suggest that if the material were kept at a constant temperature until all the moisture had

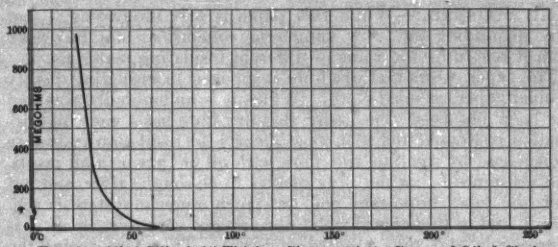

Fig. 6.—Oiled Silk .007" Thick. Characteristic Curve of Oiled Cloth.

been evaporated, the resistance of the material would then be its *true* resistance at that temperature.

(*d*) That all give a high resistance after cooling, but have little mechanical strength.

Oiled paper and oiled cloth, however, after having been heated to 220° C. and allowed to cool, not only have a high resistance, but became so firmly fixed to the brass cylinders that it was found necessary to remove them with a file.

(*e*) That it would be well to bake paper and cloth insulation to 140° C. before applying varnish or shellac.

(*f*) Referring to Fig 3, it will be seen that on decreasing the temperature the resistance increased, but the second curve does not by any means coincide with the first. On further experimenting in this direction, it was found that there is no temperature at

which the curve with falling temperature coincides with the first. This may be due to more moisture being driven out at higher temperatures which is not absorbed by cooling.

Here it may be well to mention an interesting phenomenon that occurred in connection with this investigation.

When the temperature has risen above 100° C., the zinc in the brass cylinder begins to leave its surface and combine with the copper wire wrapped about the insulation so that the wire has a brass surface and the brass cylinder a copper surface.

Owing to the limited time at the authors' disposal, they were unable to further pursue this investigation, but much remains, and any research along this line will be found full of theoretical as well as practical interest.

Discussion.

Mr. Steinmetz:—While this paper is very interesting, I fear some misleading and very dangerous conclusions may be drawn from it regarding the value of different insulating materials.

The paper shows that dry fibre is superior in insulating quality to oiled paper, or oiled cloth. While it is undoubtedly true and has been observed repeatedly that dry fibre has a very high insulation resistance, and that consequently the insulation resistance is decreased by treating the fibre with oil or japan, high insulation resistance is not the only quality to be sought after, and not even the most important one, but much more important is reliability, and in this regard wood fibre ranges very low, since it is hygroscopic, and thus absorbs moisture. Therefore during the variations of temperatures and humidity to which electric machinery is exposed in practical operation, dry fibre as insulating material is fairly sure to become moist, and thereby very dangerous.

The treatment with oil or japan is merely for the purpose of eliminating the hygroscopic quality of the fibre thereby making it a suitable insulating material.

Besides high insulation resistance, however, another quantity has to be considered, namely, disruptive strength, that is the ability of the material to resist being pierced by the voltage to which it is exposed. In medium potential circuits, as for instance, the primaries of alternating circuits, disruptive strength is generally of much greater importance than insulation resistance, and as I have shown in a previous paper, these two quantities do not always go together, but high disruptive strength may be combined with comparatively low insulation resistance, as in mica, or inversely, as in air. In disruptive strength, pure mica ranges above fibre and all other organic substances.

When coming to very high voltages, as in long distance transmission, still another phenomenon becomes of importance, which again changes the relative value of insulating materials, namely, surface leakage. Mica, for instance, while very good in disruptive strength, is not very satisfactory to guard against surface leakage, but a high potential will leak or creep over quite a long distance of mica or porcelain surface, while organic compounds are frequently much superior in this respect.

Thus insulating materials cannot be discussed generally in their relative value, but only with regard to the practical application they have to meet.

DR. F. B. CROCKER:—I agree that the paper standing alone might give rise to the dangerous conclusions of which Mr. Steinmetz has complained, but it was intended simply to investigate certain facts, as the paper itself clearly shows, if carefully read. Investigations were carried on several years ago at Columbia, by T. T. P. Luquer (*Elec. Eng.*, Dec. 28, 1892) showing the effect of moisture on these various materials, and also by Canfield and Robinson (*Elec. Eng.*, Mar. 28, 1894), showing their disruptive strength. It would, of course, be well to put all these together, and a proper comparison would include all these qualities, due weight being given to each. But it is surprising—and I think it not generally known—that the effect of oil appears to diminish the insulating qualities, particularly as soon as the temperature rises. Comparing these curves, we find that even as low a temperature as 50° C. causes the oiled paper and cloth to fall to a very low value, whereas the plain paper and plain cloth have their maximum insulating resistance, which is a very high value, at 75° C. That certainly is very striking and well worth noting. I should also call attention to the fact that probably on the continued application of any of these temperatures there is a greater effect than with the comparatively short time of treating which was the case in these experiments. Therefore, I should expect, that 50° or 60° C. applied for a long time to oiled paper or oiled cloth would bring their insulating resistance down to such a low value that they would be in danger of being broken down. I think that would explain a great many of the gradual burn-outs that occur in electrical machinery; and it remains to be seen by practical experience what the actual facts are. I know that I was very much surprised when I saw the results. I fully agree with Mr. Steinmetz that the insulation resistance is by no means the only point to be considered, nevertheless it is an important one. Now, if these materials do have a very low resistance at such a moderate temperature as 50° or 60° C., why, it would simply mean that they are not suited to work continually at that heat, and 60° C. is not now considered high. Exactly what is the best thing to do is not, of course, the intention of this paper to show, but it would indicate that we ought at least to consider this point, and that if the machines are to be worked

at a high temperature, we should make sure whether oil is a desirable thing to have. In regard to the effect of moisture, that only applies to the starting up of the machine, because when the machine gets to working, that objection disappears. I might add that the tension used in these tests was 500 volts, which is not a very high potential but is sufficient to show any very great tendency to disruption.

MR. SCOTT:—I think it is well to put some safeguards and danger signals about a paper of this kind, for taken directly on its face, it is apt to lead to erroneous conclusions. I am familiar with quite a number of tests made by Mr. C. E. Skinner, of the company with which I am connected, on very much the same lines. In his tests he has taken larger pieces of insulating material and placed them between two pieces of iron which were heated up at a slow rate, and the insulation resistance of the material was measured from time to time. The law which he has determined, if expressed on, say, curve 2, of the present paper, has its minimum where this curve has its maximum. That is, in Mr. Skinner's test there is a certain initial resistance which decreases to a minimum at 75 to 100 degrees, and after that increases. The tests to which I refer were made under what were presumed to be fairly commercial conditions in the manufacture of machines for the purpose of determining just what could be expected at different temperatures of different insulating materials. Quite a large number of materials were tested, covering about the range and kind reported in the paper. Now, either those results were wrong or these results are wrong, or they were made under different conditions. I am not prepared at this moment to say which of these is true. I do know that in the tests with which I am familiar, extending over a considerable time, and made in some cases on machines themselves, the resistance of a new machine after successive runs, as the armature or field became warmer and warmer,and also on individual pieces of different kinds of material, the same general characteristics were found in the different tests, disagreeing with those given in this paper.

The subject of oil is mentioned in the paper, and one feature which may explain the rapid decrease in the resistance of the oiled paper may be due to the fact that if there be some moisture in the paper itself and the surface be covered with a film of oil, the moisture will be confined until the temperature is raised, and then it will be vaporized and try to escape. If the surface be nearly continuous, it may contain some openings in the oil. The water will force itself out at certain points; it will pass from a hotter place to a cooler place, and the tendency will be to collect the water at some one point. The moisture, in accumulating in this way, may decrease the resistance very much at one point. Nothing is said in the paper as to the kind of oil used. There are different grades of oil, differing widely in resistance, and

often containing impurities, which may decrease the resistance very much. In the case of some oils, the resistance may be comparatively low. If the oil be heated and then cooled, it may be considerably higher, possibly moisture or impurities in the oil being driven off.

The conclusions given at the end of the paper may be justified from experiments which have been performed, but these, as it has already been stated, cover a small range, and it is going too far to draw conclusions which are general from so limited data. For instance, the first conclusion, that dry paper is a better insulation and stands increased temperature better than cloth. Better for some things, perhaps, but not necessarily for a dynamo. A high resistance galvanometer and laboratory instruments are often dangerous things in practical machinery. Another conclusion of the paper is that it would be well to bake the cloth, etc., at a certain temperature, before applying shellac and varnish. I fail to see the curve or data from which that conclusion is drawn, and I do not understand why that temperature, instead of some other or possibly lower temperature, continued for a long time, may not be a preferable one. I notice on the last page of the paper the statement that when the temperature has risen above 100° C., there seems to be some transfer in the metals which are surrounding the insulating material. It appears from this that the zinc passes from the cylinder through to the wire. If it does, that may have a very decided effect upon the insulation of the medium between the two. If there is electrolytic action, or something similar to that, by which the metal is passed through the insulating material from one side to the other, this phenomena may be very important as well as interesting. The subject is an interesting one, and I call attention to the several points in this way, in order to provoke discussion and prevent any wrong conclusion.

MR. PERRY:—Prof. Crocker called attention to the fact that if paper or cloth were heated, say, to the boiling point of a liquid, you will volatize that liquid. Those of us who have worked much in chemistry know the fallacy of that belief. I remember that in laboratory work we had considerable difficulty in drying some precipitates. Precipitated silica was one of these, and if we had much of it, it seemed almost impossible to drive off all of the water, even though we heated it to a white heat for 24 or 36 hours. In such cases our recourse was to take some small aliquot part of the total, heat this to a white heat, and then after cooling reweigh it. It was then reheated and reweighed, and this was continued until the weighings became constant. We then assumed that the moisture was all out of it. I do not know how it would be with paper, but I should suppose the same thing could be observed there. It seems to me that some of these apparent discrepancies are due to the fact that there is considerable moisture still there, and that that moisture sometimes produced chem-

ical action upon the metals upon which the paper was wound, and in being driven to the outside, carried with it the salts which had been formed. This I should consider as a possible explanation of one of the points referred to in the paper.

PROF. CROCKER:—While Mr. Scott's points are fresh in mind, I would like the opportunity of answering some of them. In the first place I think he should give us the form of those curves. There is a minimum point in the curves shown in the paper, at about 35° C., and we have a maximum point at about 75° C. Then it falls again. If we shift the curve to one side or the other, it would fully explain the statement that Mr. Scott makes. That may not be sufficient, but so far as anything he has said is concerned, it would fully explain the difference. Take, for instance, Fig. 2. The resistance at first is high, then it falls, and there is a minimum point at a little higher temperature. But when the temperature begins to reach a point that evaporates the moisture, then it rises, as I think it must. I cannot imagine that anything else could occur. These materials were taken just as they were received. They were tested on 150 different occasions, and they all gave substantially the same results. They naturally contain a certain amount of moisture which must be driven off at some temperature. Hence, there must be a maximum somewhere between ordinary temperature and a temperature of, say, 150° C., because beyond that we know the temperature will finally destroy their insulating qualities, and we must have those maxima and minima points. It is simply a question of where they occur. I can imagine that under different conditions we might have those minima or maxima occuring at different temperatures, but that general form of curve must necessarily be correct, and anyone would naturally expect substantially these results if he carefully considered the problem. If Mr. Scott remembers the form of those curves, I would suggest that he give them to us, also the temperatures corresponding. In regard to the limited range of these curves, as a matter of fact there were 102 tests made. I think it is very seldom that the INSTITUTE has a paper presented to it which is the result of so many tests as that. I imagine that papers have been read here which were the result of only one test, or perhaps none at all. In regard to the oiled paper and oiled cloth, I would say that 14 tests were made on the former and 28 on the latter; and they were made on materials furnished to us by all the prominent manufacturers in the country. In other words, we took insulating material as we found it. The tests were made entirely without favor. The surprising fact was the uniformity or general similarity that was shown by the different samples of the same class of materials. In regard to the zinc phenomenon, it was observed a year ago; and, while I did not intend to make this statement, as I should prefer to verify it a little more fully, apparently it is a fact that zinc is volatile at quite a low tempera-

ture. A very small amount of zinc vapor is formed in the receiver, and if there is a piece of copper in the same receiver, the latter will absorb the former. That is a very startling statement, perhaps, but after all it is not entirely dissimilar from other physical facts that are well known. Water has a vapor tension down to absolute zero, even ice evaporates. It is by no means necessary to have the temperature at 100° C. in order to have water vapor present. It has a vapor tension at any temperature. Therefore, we might reason by analogy that the zinc also has a vapor tension, and there is a certain amount of zinc vapor present in a space at a comparatively low temperature. It seems to me that the analogy is not carried too far, and it is only necessary to have a small amount of zinc vapor present in the receiver at any given moment, in order that the transfer may slowly occur, and during that time a superficial deposit of zinc is produced. We intended to carry the experiments further before making a positive announcement on the subject, but the discovery crept into this paper accidentally.

Mr. Scott:—The form of the curve to which I referred is in general a uniform decrease from ordinary temperature until a temperature about a boiling point is reached, the resistance falling off fairly uniformly, and after that increasing, making a fairly smooth curve at the point of minimum resistance. After that time the resistance is under a temperature of, say, 125 degrees to 150 degrees centigrade, as I recollect the curve. There was no falling off—at any rate, no falling off so marked as that shown here in the paper. The first dip in the curve as presented in the paper, as seen in Fig. 2, seems to indicate the presence of moisture which is driven off, that moisture being driven off at about 40 or 50 degrees centigrade. If that lowering of the grade is due to the driving off of moisture, the driving off has occurred much sooner and at a lower temperature in the curves here than in the curves to which I referred. That may be due to the condition of the apparatus. In the tests described in the paper, the specimens are small in amount and entirely surrounded by warm air and have great facility for throwing off moisture. In the tests to which I referred, the material was more confined—more as it is in the insulation of a machine, and the moisture does not have as great facility for passing away.

The special tests upon materials were made on somewhat the same conditions. The iron plates were about eight inches in diameter, so that the insulating material in between was fairly well confined. This may account for the difference in the temperature at which the minimum resistance occurs. After the moisture has passed off and resistance increased, the maximum is found in the curve given in the paper at something under 100 degrees, and the resistance then falls off rapidly, possibly as stated there, to a temperature above 50 degrees. At 150 degrees the resistance is at its lowest point. In the other work to which

I referred, the resistance at that temperature was as high or higher than it was in the beginning of the test. I am sorry that I have not some of these curves and more definite data in regard to them here, but will furnish some curves to be placed with this discussion later. In regard to the number of tests, I grant that 102 is more than are often supplied with the papers. Very often papers are furnished on no tests whatever. But I draw attention again to the statement that I made before, that although there are many tests here in number, they do not cover a very wide range in condition, and yet some rather broad general conclusions are drawn from them. With regard to the transfer of zinc, I inferred from the paragraph in the paper that the zinc left the cylinder under the insulating material. If it did not, but was volatized from the ends or interior of the cylinder, or some other part, then that phenomenon is disposed of.

MR. KENNELLY:—I think, if we appreciate the character of this paper, which is a very interesting and instructive one, we are not likely to form any unfair or unwarranted conclusions from the results which it shows. The subject matter is essentially a practical one, and can only be dealt with, it seems to me, from a practical point of view. The samples before us represent cellulose in a certain condition, containing certain additional materials of a coloring nature, and also additional materials of an oleaginous or varnish nature. It is also impossible to state what the specific resistance of such a material should be, except under so many incidental conditions, as to render the result, when stated, of very little practical importance. The material is fibrous, loose in character, and the structure is capable of absorbing a comparatively large volume of moisture. The resistance of thin films of this substance is given in the curves before us, under certain practical conditions. Their true resistivity is out of the question. The material contains water. Those of us who have experimented with condensers know how difficult it is to free paper entirely from the last trace of moisture. It has an absorptive power for moisture in the atmosphere which is only equalled by the avidity by which ammonia will be absorbed by water. The test is made under certain conditions in which a certain amount of water is present, and under a certain degree of pressure between the electrodes. The water will be driven off at a certain rate, and the vapor will have a secondary influence upon the results. If you vary the manner in which the experiment is made in any way, it seems to me we should look to have some corresponding variation in the results obtained; but the results, taken as they are and under the particular conditions in which they were measured, are valuable, because we find them at temperatures which are reached commercially. The specific resistances of these materials, while high, are very much lower than they are at normal temperatures. That is, I think, the prominent point, and it is a very important point. Just where the

minimum and maximum will occur in these curves depends on causes so complex that the precise shape of the curve has very little practical importance.

PROF. CROCKER:—While Mr. Scott has explained the general form of that curve, it seems to me that the discrepancy which sounded very great at first, can now be at least partially explained. The conditions in the tests described in the paper were those where the moisture had a fairly good opportunity to escape, whereas in the experiments cited by Mr. Scott the materials were placed between iron plates, and opportunity for the escape of moisture was at a minimum. I should say that the moisture in the latter case was more confined than it is in practical apparatus, because material covered with wire, is a semi-porous mass, through which the moisture can escape, but a sheet of insulating material placed between iron plates has the smallest possible opportunity for the escape of moisture. Consequently, the natural result would be that it takes a higher temperature before the moisture is driven off; therefore, the maximum point of resistance is shifted to the right, because it takes—as Mr. Scott said—a temperature of something like 150° C. before the moisture is all driven off. It simply means that it must be forced off by actual boiling, in contradistinction to mere evaporation. Now, in Fig. 2, the maximum resistance was obtained at about 75 degrees simply because at that temperature the moisture was driven off under conditions which existed in that case, when the insulating material was covered with one layer of copper wire.

MR. STEINMETZ:—It appears to me, Mr. President, that one source of possible error has been overlooked in the paper, and that is chemical action. Most of the varnishes are compounds of organic acids, which are acted upon, and which act upon copper and especially zinc. It is quite possible that the varnish has been acted upon by the zinc, and the results vitiated thereby.

[COMMUNICATED AFTER ADJOURNMENT BY MR. CHAS. F. SCOTT.]

In the discussion of the paper on "Effect of Temperature on Insulating Materials" I referred to certain tests made by Mr. C. E. Skinner. Mr. Skinner has kindly furnished the following statement of some results which he has obtained in his work in this line.

"Some time ago a series of tests were undertaken to determine the effect of temperature on the insulation resistance and breaking down E. M. F. of various insulating materials and of completed apparatus. A large number of insulating materials, including paper, cloth, etc., both in the treated and untreated forms, were tested. The tests on completed apparatus were made on armatures, fields, converters, etc., these pieces of apparatus being treated in various ways before the tests were made.

(1) *Tests on Insulating Materials.*—Various methods of making these tests were tried. The apparatus illustrated in Fig. 1 was finally adopted for standard tests as being best suited for practical work. This piece of apparatus consists of two similar parts, the two parts forming the plates between which the insulating material is placed when tested. These plates are 10 inches in diameter and are carefully surfaced. Each part is made of two separate pieces of cast-iron, fastened together as shown, and wound with a coil of asbestos covered wire. The heating of the apparatus is effected by sending an alternating current through the two coils in series. The heating results from the eddy current and hysteresis loss in the iron as well as from the copper loss in the coil. The rate of heating can be controlled easily by means of a suitable rheostat in circuit with the coils, the mass of iron in the heater being sufficient to prevent sudden changes of

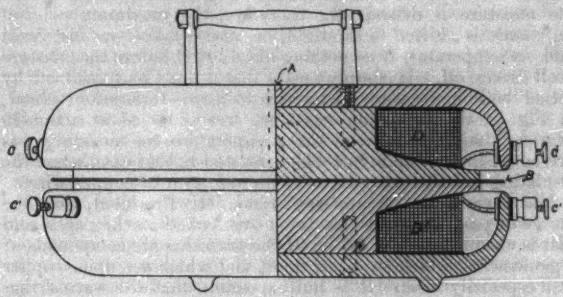

FIG. 1.

temperature from outside causes. The insulation resistance of the samples was measured in all cases by means of a high resistance voltmeter on a 500-volt circuit, all wires of the heating circuit being disconnected when the insulation measurements were made. This method of measurement was adopted on account of the portability of the apparatus and the facility with which the measurements could be made, a complete measurement of insulation resistance requiring from 10 to 15 seconds. Ordinarily the time occupied in making a complete test on a sample of material was from one to two hours. Insulation resistance readings were made at frequent intervals.

In Fig. 2 is given a curve obtained from tests on a piece of untreated paper which is largely used for insulating purposes. As will be seen, the minimum resistance is reached at slightly below 100 degrees C. From this point the resistance rises rapidly until it reaches a point too high to be measured with the

apparatus used. The absolute value of the insulation resistance of any material of this class, depends on the amount of moisture in the material at the start, the rate of heating and the chance for the escape of moisture during the test. The temperature at which the insulation resistance is lowest depends slightly on the

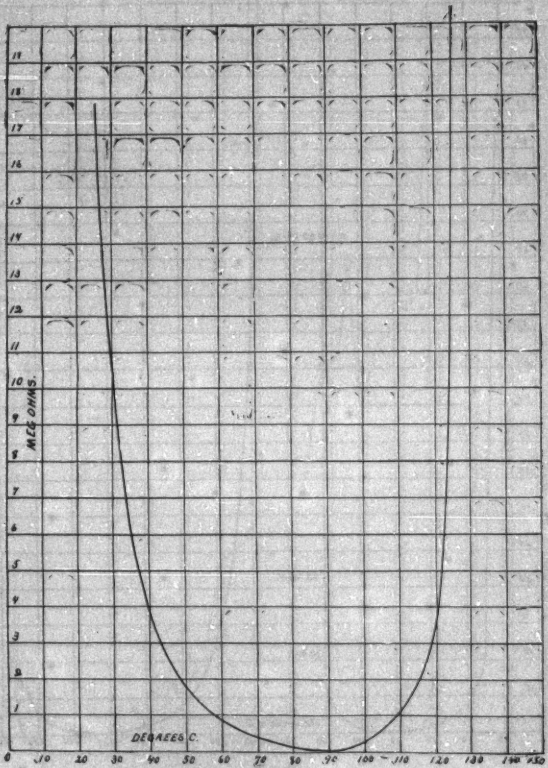

FIG. 2.

rate of heating. The curve shown in Fig. 2 is characteristic of all materials of a fibrous nature which do not contain chemicals or materials which are readily changed by heat. The absolute values of the insulation resistance for different materials or even

for two samples of the same material are rarely the same, but the general shape of the curve has been found to be practically the same for all such materials, the tests extending over a period of several years and being made in many ways.

The curve for treated material, such as oiled-paper, is similar

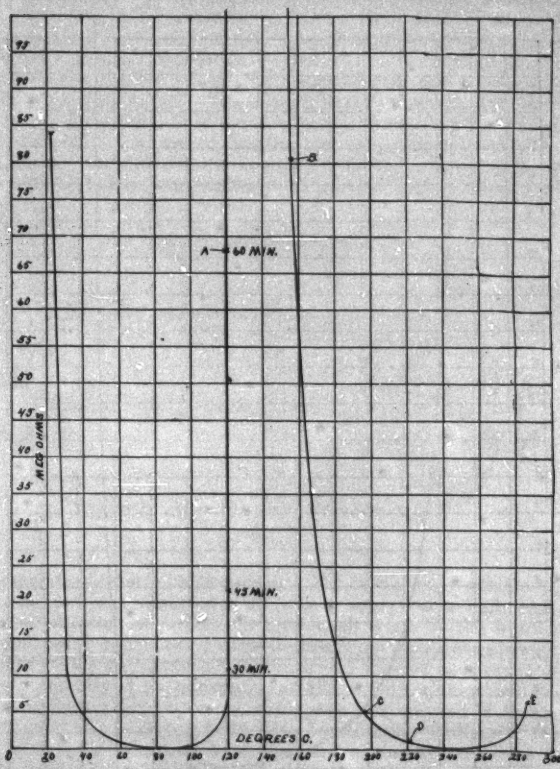

FIG. 3.

to the curve shown in Fig. 2. The absolute value of the insulation resistance depends largely on the drying of the material before treatment. Samples of cloth which were treated with linseed oil after being thoroughly dried and then the oil baked on, do not at any time show a very low insulation resistance, even at a temperature of 150 degrees C.

In Fig. 3 are shown curves for a sample of .015″ calendered press-board. This press-board is made of a mixture of scrap paper and rags. The test on this sample was made as follows: The temperature was gradually raised to 120 degrees C., the time occupied in reaching this temperature being 30 minutes. The

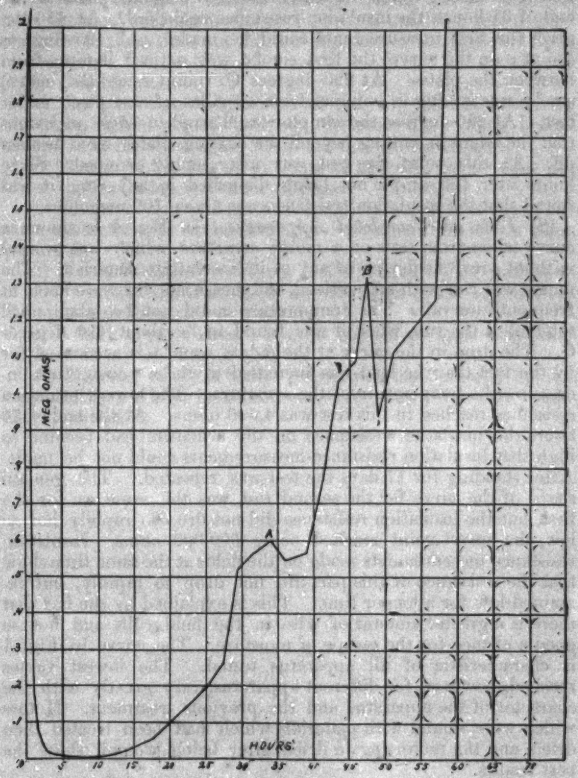

FIG. 4.

temperature was maintained constant at 120 degrees for 31 hours. At the end of this time the temperature was increased to 280 degrees. At the end of 30 minutes the insulation resistance had fallen from 85 megohms to less than one megohm and again

risen to about 12 megohms. The lowest point reached was .032 megohms. At the end of 70 minutes the insulation resistance had become too great to be measured by the apparatus at hand. Frequent readings were taken during the 31 hours' run at 120 degrees C., but at no time was it possible to measure the insulation resistance. When the temperature was again raised at the end of 31 hours, the insulation resistance again fell. At 150 degrees the first measurements could be made. At 195 degrees (point C on the curve) the first smoke was noticed issuing from between the plates. At 220 degrees C. (point D on the curve) smoke was issuing in volumes from all sides of the piece under test. At 280 degrees the sample was charred to such an extent that the edges extending beyond the heating plates were broken off. At this point the test was unavoidably stopped. Sixty hours later, the sample not being disturbed in any way, it was found that the insulation resistance was above 100 megohms.

(2) *Tests on Completed Apparatus.*—In Fig. 4 is shown a curve taken from tests on a motor armature which was wound without previous drying of any of its insulating materials. The motor was run with an overload, and measurements were made at frequent intervals. The temperature could not be taken until the end of the run, when it was found to be about 110 degrees C. The drop in the curve at the points A and B is accounted for by the fact that the load was increased at these points, thus increasing the temperature of the armature. The lowest insulation resistance reached in this test was 4,500 ohms. At the end of 70 hours the insulation resistance on the armature had become so high that insulation resistance measurements could not be made. After standing for 17 days the test was repeated. The general shape of the curve for the second test was the same as for the first, but the insulation resistance did not drop so rapidly nor so low, the lowest point reached being 500,000 ohms. Insulation resistance measurements made on the fields at the same time show that the resistance of this part did not drop so rapidly, but remained low for a longer time. This is explained by the fact that there is a greater amount of wire in the field coils and not so good a chance for the escape of moisture. The curve in Fig. 4 is characteristic of all apparatus tested. The lowest values reached, however, for different apparatus, vary greatly with the character of the apparatus and the previous treatment. Motors which were wound with materials which had been treated then dried, and the motors again dried after being wound, show the best results.

(3) *Relation Between Breaking Down E. M. F. and Insulation Resistance.*—An attempt was made to establish the relation between the breaking down test of insulating materials and their insulation resistance. For this purpose samples of paper which gave a very uniform breaking down test in the normal state, were heated up until the insulation resistance reached a cer-

tain predetermined amount, when the breaking down test was quickly made. It was found impossible to establish any definite relation between the two, even for a given material. It was found, however, that a low insulation resistance usually meant a low breaking down test, but a low breaking down test did not necessarily mean a low insulation resistance. These two tests may be compared to the chemical analysis and the tensile test of iron. A poor chemical analysis means poor physical qualities, but a good chemical analysis does not indicate whether or not there are flaws in the metal.

(4) *Conclusions.*—

(*a*) The insulation resistance of all ordinary fibrous insulating materials, such as paper, cloth, etc., decreases upon being heated up and then increases again when the moisture is expelled.

(*b*) Continued heating of 31 hours at 120 degrees C. does not lower the insulation resistance of paper.

(*c*) The insulation resistance of completed apparatus shows the same characteristics as the insulation resistance of materials taken separately.

(*d*) A low insulation resistance is not necessarily an indication of poor insulation, but probably an indication of the condition of the apparatus in regard to moisture.

(*e*) A high E. M. F. should not be applied to apparatus when the insulation resistance is low.

(*f*) Material which is badly deteriorated mechanically by heat may still have a high insulation resistance, but very poor insulating qualities."

A paper presented at the 13th General Meeting of the American Institute of Electrical Engineers, New York, May 20th, 1896. President Duncan in the Chair.

AN EXPERIMENTAL STUDY OF ELECTRO-MOTIVE FORCES INDUCED ON BREAKING A CIRCUIT.

BY F. J. A. McKITTRICK, WITH AN INTRODUCTION BY DR. EDWARD L. NICHOLS.

Preliminary Note.

The method described by Mr. McKittrick in the following paper is one that has been developed by successive steps to meet the requirements of the study of fluctuating electric currents. As long ago as 1880 Joubert[1] introduced what has since proven an extremely useful method in the study of alternating currents, namely, that of instantaneous contact. This method was used independently and almost simultaneously by Thomas and Geyer[2] and has since been developed and perfected by Duncan[3], Ryan[4], Bedell[5] and many others. It has remained in use ever since and has been of the highest service. A variety of methods for the recording of current curves, principally by the aid of photography, have been added. The first attempt in this direction was made by Fröhlich[6] in his well-known experiments with a mirror mounted upon the diaphragm of a telephone. The photographic method has been further developed by Blondel[7] and others. In 1892 Moler[8] constructed a galvanometer, the needle of which had a period so rapid as to make it possible to follow fluctuations, the period

1. Joubert, *Journal de Physique* 1880.
2. Thomas and Geyer; A. I. E. E., vol. viii, p 393, vol. ix, p 263.
3. Duncan, Hutchinson and Wilkes; *Electrical World*, vol. xi, p 160.
4. Ryan; A. I. E. E., vol. vii, p 1.
5. Bedell, Miller and Wagner; A. I. E. E., vol. x, p 498.
(For further references see the last named paper.)
6. Frohlich; *Elektro-technische Zeitschrift*, vol. x, p 345.
7. Blondel; *La Lumiere Electrique*, vol. xli, p 401.
8. Moler; A. I. E. E., vol. viii, p 324.

of which did not exceed one one-hundredth of a second. In this instrument, as is well known, the record was made by the movement of a pointer over the surface of a smoked cylinder. Since the construction of the Moler curve-writing galvanometer, Hotchkiss[9] has busied himself with the development of an instrument the needle of which has a much higher rate of vibration. By means of this galvanometer, which is described in the succeeding paragraphs of this paper, a great variety of curves have already been obtained, and its application to the problems studied by Mr. McKittrick is herewith presented to the INSTITUTE in the belief that it will serve to illustrate the usefulness of the method in question.

———o———

Since the days of Faraday, many experimental studies have been made of induction currents. The list of experimenters is a long one including, in Europe, the leading physicists of each generation, while on this side of the Atlantic the researches of Henry have connected his name permanently with electro-magnetic induction. Nearly all the researches have been made by the aid of a secondary circuit. Mr. F. E. Millis has however, photographed the extra current in the circuit itself when the E. M. F. is suddenly removed, and has shown that it has a physical as well as a mathematical existence. (*Phys. Rev.*, vol. iii, No. 17.) One of the earliest forms of circuit by which Faraday illustrated the existence of the extra current of self-induction is shown in Fig. 1, in which C is a coil containing iron, such as an electro-magnet, through which a current is flowing from a battery A; B is another circuit containing a galvanometer connected in parallel with C at the points F and G. By blocking the needle of the galvanometer so that it is not deflected by the battery current flowing from F to G, it will indicate, on breaking A, the presence of a current flowing from G to F induced, as we know, in the branch C. That this induced current may exceed in intensity the original current flowing through B may be simply shown by placing in B an incandescent lamp. Under suitable conditions, while the steady current from A is flowing, the lamp will remain quite dark, but on breaking the circuit A, it will flash into incandescence.

The present paper is an attempt to describe the results of an introductory experimental study of the induction phenomena exhibited when the above form of circuit is broken. The results

9. Hotchkiss and Millis; *Physical Review*, vol. iii, p 49; also F. E. Millis, *Physical Review*, vol. iii, p 351.

presented must be regarded as chiefly illustrative, but it is hoped that they may be found interesting, perhaps useful, to the INSTITUTE, since the fields of all dynamos and motors are enormous electro-magnets and at every change of the current through them, E. M. F.'s are developed, a knowledge of which is essential to the electrical engineer.

In the galvanometer for photographing alternating current curves (*Physical Review*, vol. iii, No. 13) which has been brought

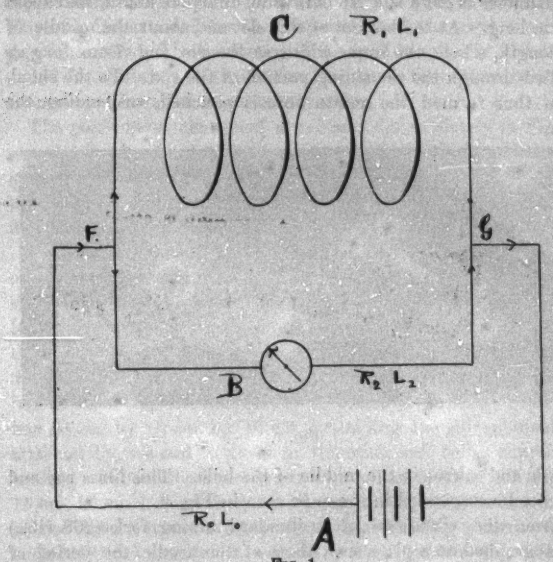

FIG. 1.

to such a high state of perfection by Messrs. Hotchkiss and Millis, we have an ideal instrument for studying such rapidly varying currents as accompany a break in a circuit. It was by the aid of such an instrument that the present work was done.

In the article cited above, the construction of this galvanometer is fully described. Since, however, the form used by the writer was modeled after later designs of Mr. Hotchkiss, it may be well to outline briefly the construction of the principal parts.

The apparatus in question is a photographic galvanometer.

From a minute mirror attached to an equally minute needle, light from some source is reflected to a narrow slit past which a photographic plate is dropped, thus recording any motion of the needle. In the experiments to be described, the needle used consisted of a minute piece of soft iron 1.65 mm. by 1.07 mm. and .07 mm. thick, to which was attached a mirror .53 mm. by .42 mm. made from a silvered microscope cover glass. The needle and mirror are mounted on a quartz fibre. Lengthwise of a brass rod .32 cm. in diameter is cut a slot .16 cm. wide, of equal depth, and about 3 cm. long. At the bottom of this slot and about the middle of its length, a hole, the same width as the slot and .7 cm. long, is drilled through the remaining portion of the rod. To the shoulders thus formed the quartz fibre is attached, suspending the

FIG. 2.

needle and mirror in the middle of the hole. This brass rod and the needle suspended in it can be seen in Fig. 2.

From the vibrations of a standard tuning fork (768 vibs.) photographed on a plate with those of the needle, the period of the needle is easily found. It is 2656 complete vibrations per second.

The general construction of the galvanometer can be seen from Fig. 2. The permanent horse-shoe magnet has a length of 20 cm. and a total width of 10.8 cm. A block of wood 10.8 cm. by 4.9 cm. by 1.6 cm. slips over the ends of the magnet as shown, while in a second block 10.8 cm. by 4.9 cm. by 2 cm. is a groove 2.5 cm. wide and 1.5 cm. deep, carrying the tapering pole-pieces as shown. The two coils of the galvanometer are fixed by paraffin in holes 2.5 cm. in diameter and 1.7 cm. deep,

bored, one in each block, so that one coil is flush with the surface of the first block, and the other with the bottom of the groove in the second. These two blocks are placed face to face and fastened by screws. The brass wire containing the needle is slipped vertically down between the coils and pole-pieces as shown. Connection between the two coils is made by a spring, the other terminals being connected to binding posts.

The coils of the galvanometer were wound with No. 36 B & S. copper wire on a standard form used by the mechanician of the Physical Department for the construction of the most sensitive galvanometers. The resistance of the coils in series is 270 ohms at 18° C., while the self-induction is so small that attempts at determining it have led to negative results.

The pole-pieces mentioned above and shown clearly in Fig. 2, were made of soft iron 2.5 cm. wide and .5 cm. thick. Each was 3 cm. long and tapered to a tip .5 cm. by .2 cm. They fitted tightly into the groove and were adjusted by microscope to equal distances from the needle.

In order to protect the photographic plate from light, the part of the apparatus shown in Fig. 3, was constructed. The vertical slide, in which the plate drops, is 18 cm. by 7.5 cm. and 90 cm. long. In the inside of the slide, two cleats extend the length of the box between which and the back of the box the plate-holder drops. One cleat extends only to within 23 cm. of the top of the box in order that the holder may be placed in position. A second box 48 cm. by 18 cm. by 10 cm. containing the galvanometer is attached by one end to the slide, the other end being supported by legs. Where the boxes are in contact, an opening 1.7 cm. by 15 cm. is cut through both, and across this opening on the inside of the slide, is pasted a piece of cardboard having a narrow horizontal slit 12.7 cm. by .05 cm. and through which the reflected light from the galvanometer passes to the plate. Light passes to the mirror of the galvanometer through a vertical slit in a shutter shown clearly in Fig. 3. This shutter is adjustable about a vertical axis at the end of a box.

The galvanometer is so supported that it is adjustable by hand about a vertical axis passing through the needle, while a screw at the end allows delicate adjustments to be made about a horizontal axis. Before dropping, a brass catch holds the plate holder in position from which it can be released at will, while a cushion of waste at the bottom of the slide diminishes the shock of the

drop and a small spring catch prevents a rebound. The whole apparatus is painted a dead black, while felt attached to the doors serves to keep out all useless light.

A small mirror which is attached to the galvanometer itself, and is adjustable, was used to trace out a reference line as seen

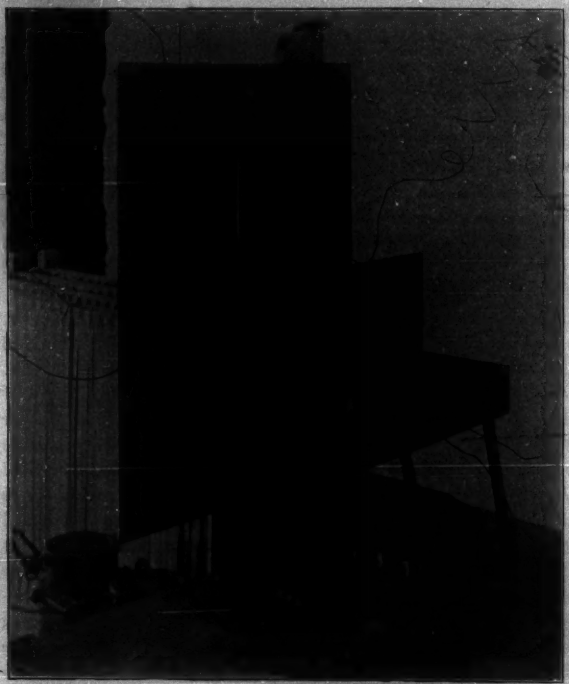

FIG. 3.

on the curves. By it an exact zero line could be obtained but only with great care in adjustment. Since in general an absolute zero line is not necessary, this mirror was usually only adjusted to trace an approximate zero line.

The calibration curve for the galvanometer is given in Fig. 5.

The arrangement of apparatus during the investigation is shown

in Fig. 4, in which C is an electro-magnet through which a current is flowing from a battery in the branch A; B represents the galvanometer placed in series with a high resistance in parallel with C at the points F and G; L is the arc lamp, and S the slide in which the plate drops; H is a form of circuit breaker placed in A and controlled by an electro-magnet operated by an auxiliary circuit. When a current is flowing in this auxiliary circuit, the terminals in the breaker are held in contact against the force of a spring and the circuit through C is complete. The plate holder in dropping, operates a trip which breaks this auxiliary circuit,

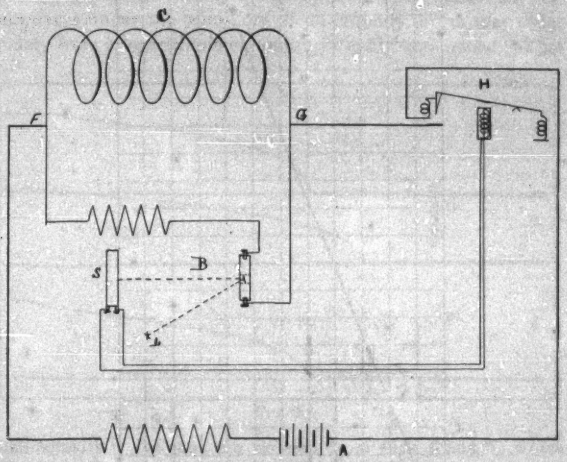

FIG. 4.

and hence the main circuit, the effects of the break being recorded on the plate.

The circuit breaker used, consisted of a modified form of telegraphic sounder. The frame-work which usually limits the motion of the armature lever was removed, and the lever itself lengthened. To the end of this lever, at right angles to it, and in a vertical plane, was fastened the metal forming one terminal, to which was attached a wire carrying the current. This wire was so flexible that it did not materially interfere with the motion of the lever. The upper terminal consisted of a strip of metal

about .04 cm. in thickness, tapering to a width of about .2 cm. The other terminal was a sheet of the same metal about 5 cm. square, placed horizontally beneath the upper terminal.

The source of light used was an arc lamp fed by hand, and enclosed in a box, in the front of which a vertical slit, .5 mm. in width, allowed the light to pass to the mirror. The carbons were

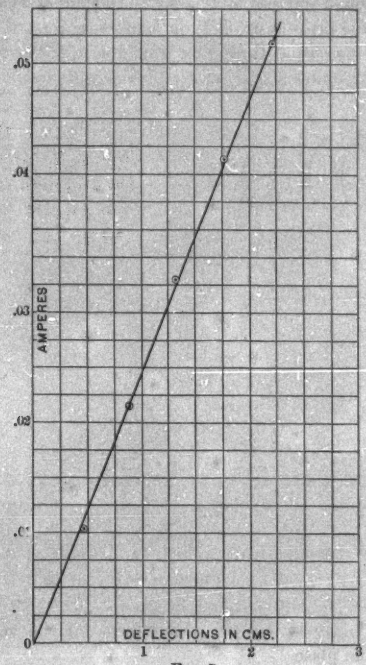

FIG. 5.

tilted at an angle of about 30° in order that the brightest light from the crater might be reflected to the plate.

Since the phenomena which we wish to study occurs when the circuit A is broken, it is well to examine what happens when a circuit through which a current is flowing is opened, and by what law the current falls to zero.

As we open a metallic switch, for example, an arc is formed

through which the current continues to flow until the terminals of the switch become separated so far that the E. M. F. of the circuit is unable to force a current across. The spark then breaks. What actually occurs in the formation and rupture of such an arc is unknown. The nature of the arcs so formed must vary under different conditions of breaking, and the law by which the current reaches zero in each case must vary with the arc so formed and its time of duration.

It has been established theoretically and verified experimentally, that, on the removal of the impressed E. M. F. from a circuit, the current reaches zero by a logarithmic curve. That the current curve under the conditions of an ordinary break may differ widely from a logarithmic curve can be easily understood. That

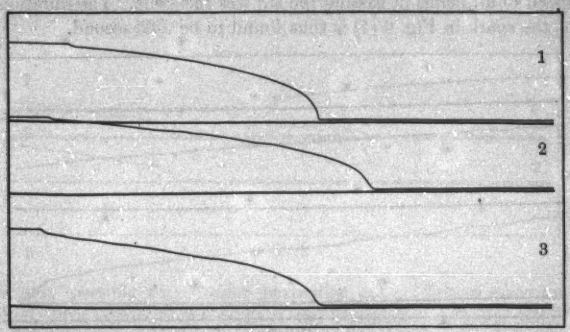

FIG. 6.

such actually is the case, can be seen from Figs. 6 and 7, which show the dying away of the current, when a simple circuit is broken. These curves were obtained by connecting the galvanometer just described, in parallel with a non-inductive resistance of 3.385 ohms, placed in series with the coil c used during the present investigation, and breaking the circuit in the manner described above.

In Fig. 6, the three curves represent a "break" under different conditions. The curves are traced from left to right. The three straight lines are the three reference lines, approximately zero lines. Beginning at the left, the straight part of each curve represents the steady deflection of the needle, the distance of this deflection from the zero line being proportional to the strength

of the current. The point at which the "break" begins is clearly marked by a slight notch. From that point the curves fall away approaching the reference line quite slowly at first but abruptly at the end. From the point where the "break" ends, the curves run parallel to the reference line.

Fig. 6 (1) is a "break" in which the terminals of the circuit-breaker are of copper, E, the E. M. F. of the circuit is 170 volts, L, the self-induction, .029 henrys and I, the current flowing before the "break," 5.2 amperes. The time taken by the spot of light to trace out any part of the curve is found by comparing the curve with the vibrations of a tuning fork of known pitch photographed on a plate dropping at same speed. Since in all cases the plate holder fell quite freely, it may be assumed that the speed of all plates in passing the slit was the same. The duration of the spark in Fig. 6 (1) is thus found to be .065 second.

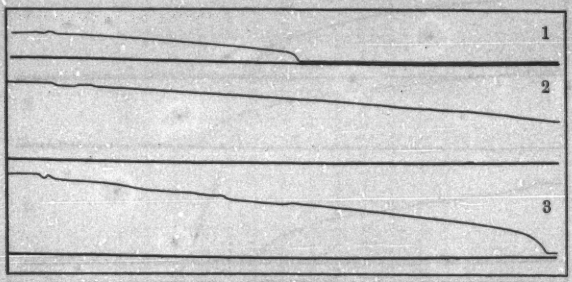

FIG. 7.

Fig. 6 (2) shows a "break" when the breaking terminals were of brass, all other conditions remaining as in (1). The time of duration of the spark is .075 second.

Fig. 6 (3) shows a "break" under the same conditions as (2), except that the spring of the circuit-breaker is strengthened, thus separating the terminals more quickly, and hastening the destruction of the arc. The time of duration of the spark is .068 seconds.

Fig. 7 (2) and (3) show "breaks" with brass and copper terminals, respectively, in which the current is the same as in Fig. 6, but the spring of the circuit-breaker, weaker. The spark in (2) lasts longer than one-ninth of a second, so that its ending is not recorded in the plate. In (3) the terminals are of copper and the spark again ends more quickly than with brass terminals.

Fig. 7 (1) shows a "break" with brass terminals, the current being only 1.5 amperes, while other conditions remain as in (2) and (3).

Fig. 8 (1) and (2) show current curves for a "break" from zinc terminals. The irregularities in the curves are characteristic of all "breaks" from zinc terminals, and seem to indicate that the arc formed is very irregular.

The current curves just discussed can, however, be only accepted as illustrative of one method of breaking the circuit.

It is clear that in order to follow theoretically the instantaneous values of the induced currents in the form of circuit shown in Fig. 1 when A is broken, the current curve during the break should be known. Since, in general, this curve is not known, it

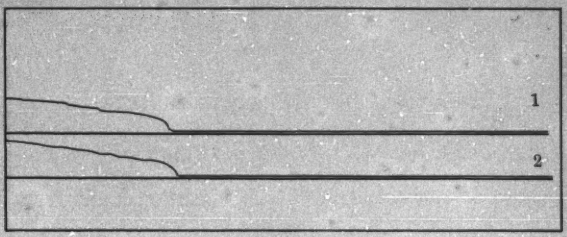

FIG. 8.

is only possible to consider particular cases. Let us examine, then, what occurs under perhaps the simplest conditions which can be imagined.

Consider again the circuit in Fig. 1. Let R_0 L_0 be the resistance and self-induction of the branch A, and let R_1 L_1 and R_2 L_2 have the same meaning for C and B, respectively. Let L_0 be zero, for simplicity, and $L_1 > L_2$. During the break in A, we shall have three sources of E. M. F. in this circuit, viz., the E. M. F. of the battery A, which we shall call E, and the two E. M. F.'s of self-induction; one in C and one in B. Let us think of the current produced in any branch by each E. M. F. as separate from that produced by each of the others. The resultant actual current at any instant in any branch will be the resultant of the three hypothetical currents generated respectively by the three E. M. F.'s. That it is legitimate to think of each E. M. F. as generating its own current independent of the

action of other E. M. F.'s in the circuit, is evident when we consider that the solution of any differential equation for the current in any circuit in which there are several sources of E. M. F. results in an expression involving the sum of different terms, each term representing the value of a current produced by a corresponding E. M. F.

Let the current due to E be I_0, dividing into I_1 through C, and I_2 through B. Let I_1^1 be the current produced by the E. M. F. of self-induction in C, and dividing through the branches B and A, and let R_1^1 and L_1^1 be the equivalent resistance and self-induction of the path of this current. Let I_2^1 be the induced current in B, and L_2^1, R_2^1, the equivalent self-induction and resistance of its path.

Suppose now that when A is broken, the character of the break

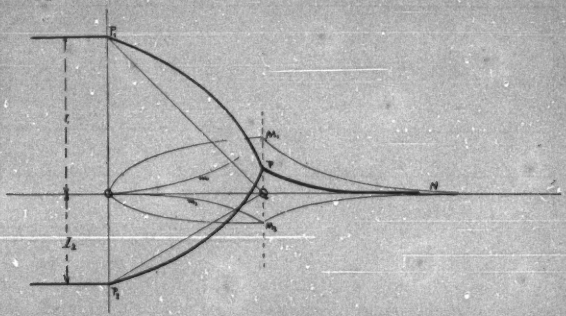

FIG. 9.

is such that I_0 decreases uniformly during T the time of duration of the spark. If we plot currents as ordinates and times as abscissæ in Fig. 9, we may represent the decrease of I_1 and I_2 by the straight lines P_1 Q and P_2 Q respectively, where O Q represents T, the time of the duration of the spark.

We have during that time T, $L_1 I_1$ lines of force in the field of C, due to I_1, uniformly removed, and hence we have a uniform E. M. F. acting in the circuit C during that time, equal in magnitude to $\frac{L_1 I_1}{T}$. At any instant, then, we have for the instantaneous value of the induced current

$$i_1^1 = \frac{E}{R_1^1}\left(1 - e^{-\frac{R_1^1 t}{L_1^1}}\right) = \frac{L_1 I_1}{T R_1^1}\left(1 - e^{-\frac{R_1^1 t}{L_1^1}}\right),$$

and if R_1^1 and L_1^1 were constant, i_1^1 would increase according to a logarithmic curve.

Now R_1^1 is not even approximately constant. For

$$R_1^1 = R_1 + \frac{R_0 R_2}{R_0 + R_2},$$

and R_0 is increasing rapidly. I_1^1 may be represented, then, by some curve $O M_1$, whose form will vary with the character of the spark, rising to a maximum at the end of the time T, and from the point M_1 dying away according to a logarithmic curve $M_1 N$, whose equation is

$$i_1^1 = i_{1\,\text{max.}}^1 \times e^{-\frac{R_1 + R_2}{L_1 + L_2} t}.$$

Similarly, we can represent the induced current I_2^1 in B by the curve $O M_2$, during the time of the spark, and $M_2 N$ afterwards.

The current through C, at any instant, is the resultant of I_1, and I_1^1, at that instant, and the part of the current I_2^1 which is then flowing through C. Denoting the instantaneous value of this resultant current through C by i_c, we have

$$i_c = i_1 + i_1^1 - \frac{R_0}{R_0 + R_1} i_2^1.$$

From this equation we see that since, by assumption, $i_1^1 > i_2^1$, i_c will always be positive. When $i_1 = 0$, then we have $\frac{R_0}{R_0 + R_1}$ unity, and $i_c = i_1^1 - i_2^1$. From that instant at any time t

$$i_c = (i_1^1 - i_2^1)_{\text{at end of time } T} \times e^{-\frac{R_1 + R_2}{L_1 + L_2} t}.$$

If the curve $O m_2 M_2$ represents the proportion of i_2^1 which flows through C, i_c may be plotted by adding at each instant the coördinates of the curves $O M_1 N$, $P_1 Q$ and $O m_2 M_2$ taken with their proper signs. The resultant curve for the current flowing in C will be $P_1 P N$.

Similarly for i_B, the instantaneous value of the resultant current in B, we have

$$i_B = i_2 + i_2^1 - \frac{R_0}{R_0 + R_2} i_1^1.$$

Since i_1^1 is increasingly greater than i_2^1, this equation shows that i_B gradually decreases and that at some time when

$$i_2 + i_2^1 = \frac{R_0}{R_0 + R_2} i_1^1,$$

i_B is zero. After that i_B is negative and gradually increases to a maximum at the end of the time T. i_2 is then zero, R_0 infinite, $\frac{R_0}{R_0 + R_2}$ unity, and $i_B = i_2^1 - i_1^1$. From that instant i_B decreases to zero according to the equation,

$$i_B = (i_2^1 - i_1^1)_{\text{at end of time } T} \times e^{-\frac{R_1 + R_2}{L_1 + L_2} t}.$$

After the ending of the spark, we thus have i_B equal in magnitude to i_c. If

$$\frac{R_0}{R_0 + R_2} i_1^1$$

is represented by the curve $O m_1 M_1$, i_B will be represented by the curve $P_2 P N$ whose ordinates at any instant will be the sum of the ordinates $P_2 T$, $O M_2 N$ and $O m_1 M_1 N$, taken with their proper signs.

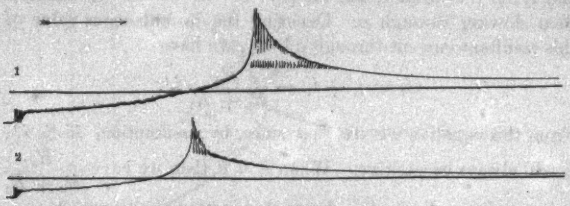

FIG. 10.

The curves shown in Fig. 9 must be accepted as merely illustrations of the form the current curves might assume under certain conditions. Since they are obtained on the assumption that the current I_0 dies away uniformly, it is scarcely to be expected that the photographs obtained of the current through B during the "break" would agree in detail with the curve drawn above. Since in the present investigations the resistance of the branch B was 300 times that of C, no attempt could be made to draw the curves in Fig. 9 to represent the magnitude of the currents in B and C during this investigation without destroying the clearness of the figure.

It has been difficult to obtain photographs of I_B which are distinct enough to reproduce for publication. For the current curve is irregular, and since the needle possesses some inertia, the very sudden changes in the current produce vibrations which

are difficult to photograph. It has therefore been necessary, in order to reproduce the faintest of these curves, to print from positives on bromide paper and sketch in the outline obtained.

Fig. 10 (1) (2) show current curves for the branch B, reproduced in this way. The curves are traced from right to left. The straight part of each curve at the beginning is the steady deflection

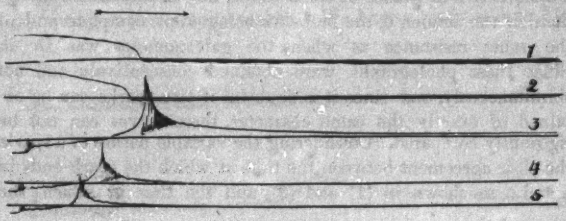

FIG. 11.

of the needle from zero, representing the current flowing before the break. This deflection was to the left, and hence appears below the zero line, as viewed in Fig. 10. The point where the break begins is clearly marked by a sudden deflection toward the zero line. From that point the curve dies away to the zero line, crosses it, rises to a maximum on the other side, and from there

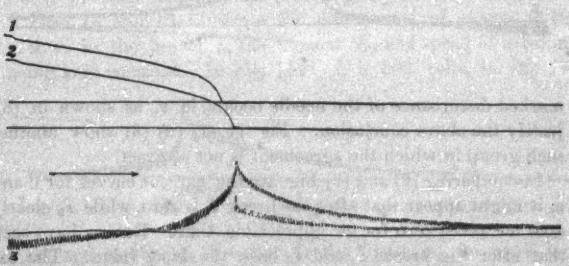

FIG. 12.

falls to zero by a curve logarithmic in form. The marked vibration of the needle at or near its point of maximum deflection is striking, and shows that at that instant the current suddenly changes in magnitude.

From the curves obtained in Fig. 9, we see that the current curve for B undergoes such a change at the point P, where we

have supposed the spark to end, and we therefore might conclude that these violent vibrations of the needle in Fig. 10 would mark the ending of the spark in the branch A. This conclusion is supported by Fig. 12, in which (3) represents another current curve for the branch B, while (1) and (2) show current curves for A and C, which were obtained by shunting the galvanometer across a non-inductive resistance of 3.385 ohms, first in the branch A, and then in the branch C, the branch B being kept complete and of the same resistance as when the galvanometer was in it. Since these photographs were obtained consecutively and not simultaneously, and since it is doubtful if two sparks can be obtained of exactly the came character, these curves can not be rigorously compared. Considering the variable nature of a spark, the close agreement between the time at which the spark ends in A and C, as shown in (1) and (2), and the time at which the

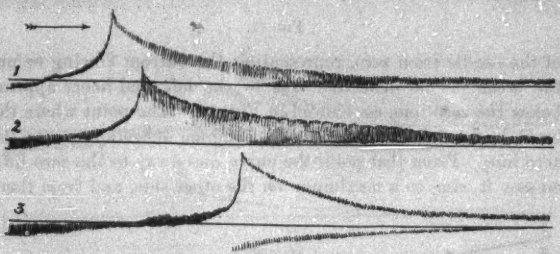

FIG. 13.

marked disturbance of the needle occurs in B, as shown in (3), justify the above conclusion. Fig. 11 (1) (2) (3) show another such group in which the agreement is not so exact.

In comparing (2) and (3) Fig. 12, the current curves for C and B, it might appear that after the break I_c is zero, while I_B clearly does not reach zero for an appreciable time. But we have seen that after the break, I_c and I_B have the same value! The explanation of this apparent inconsistency is found in the fact that the scale to which I_B is traced is twenty times as great as that to which I_c is traced, and hence a current which is represented by a considerable ordinate in the one case, is scarcely noticeable in the other.

Figs. 10 and 11 (3) (4) (5) illustrate the effect on the current through B, of varying I_0, the current through A at the instant of

breaking the circuit, other conditions of the circuit being kept as constant as possible. In Fig. 11 (5), I_0 is .75 amperes; in (4), 1.5 amperes; in (3), 2.25 amperes, and in Fig. 10 (2) and (1), I_0 is 3.5 and 5.2 amperes, respectively. The curves show us that increasing the current I_0, increases the duration of the spark, and the maximum point to which the current curve I_B rises.

Fig. 13 illustrates the effect on I_B of increasing the strength of the spring in the circuit-breaker. We have already seen in Figs.

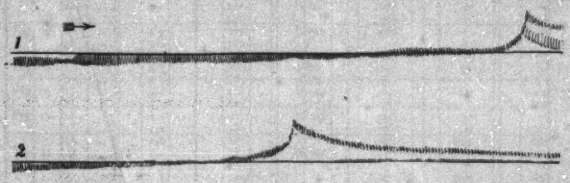

FIG. 14.

6 and 7 that increase of the strength of the spring in the circuit-breaker decreased the duration of the spark. The curves (1) (2) (3), taken with decreasing strength of the spring, further illustrate this. No marked effect on the height to which I_B rises can be noticed. As nearly as the curves can be measured, (2) and (3) rise to the same height, while (1) is slightly less than either.

Figs. 14 and 15 illustrate the effect on I_B of change in the E. M. F. in the branch A, the current I_0, and speed of breaking being kept constant. In Fig. 14 (1) E is 300 volts, in (2), 170

FIG. 15.

volts, and in Fig. 15, 58 volts. In the first case, the spark lasts .115 second; in the second, .066 second, and in the third, .018 second. The height to which I_B rises decreases as E increases, being .4, 1.25 and 1.4 cms. above the zero line in the three cases, respectively.

Since the resistance of the branch B was very large compared with that of C, the one being 1570 ohms and the other 5.815 ohms, and since its self-induction was negligible, the current

through the galvanometer B may be taken as a measure of the difference of potential between the points F and G (Fig. 4). Since this potential difference after a short time is largely due to the induced E. M. F. in the branch C, and, after the break, wholly due to it, the current curve for B may be taken as indicating the

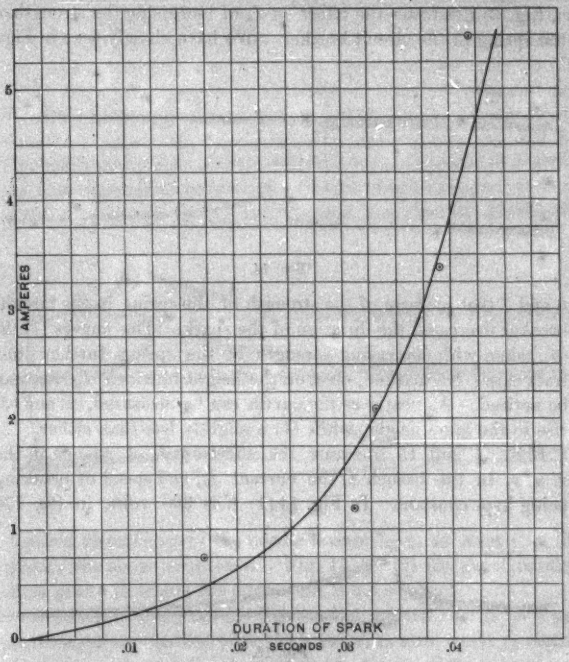

FIG. 16.

variation of this induced E. M. F. during the break, and as approximately representing it in magnitude.

From the curves shown above, we gather that the arc formed by a break is exceedingly variable in character and duration, and that the E. M. F.'s induced by the break vary with the arc formed.

We note that (*a*) the duration of the arc depends upon:

I. The current flowing at the instant of break. The variation

of the duration of the arc with the current, as calculated from Figs. 10 and 11 (Table I.), is shown graphically in Fig. 16.

TABLE I.

No.	I_0 Amperes.	E Volts.	Terminals of Circuit Breaker.	Duration of Spark, Seconds.	Maximum P. D. at points F & G Volts.	Maximum Current Flowing Through B Amperes.
Fig. 6 (1).....	5.2	170	Copper	.065	—	—
" (2).....	5.2	170	Brass	.075	—	—
" (3).....	5.2	170	"	.068	—	—
Fig. 7 (1).....	1 5	170	Brass	.066	—	—
" (2).....	5.2	170	"	—	—	—
" (3).....	5.2	170	Copper	.115	—	—
Fig. 8 (1).....	2.15	169	Zinc	.042	—	—
" (2).....	2.15	169	Zinc	.046	—	—
Fig. 10 (1).....	5.5	125	Brass	.047	62.0	.042
" (2).....	3.4	125	"	.061	57.0	.038
Fig. 12 (1).....	4.2	125	Brass	.055	—	—
" (2).....	4.2	125	"	.057	—	—
" (3).....	4.2	125	"	.057	40.5	.027
Fig. 11 (1).....	2.1	125	Brass	—	—	—
" (2).....	2.1	125	"	—	—	—
" (3).....	2.1	125	"	.031	40.5	.033
" (4).....	1.2	125	"	.026	46.5	.031
" (5).....	.75	125	"	.015	95.5	.017
Fig. 13 (1).....	2.75	125	Brass	.024	30.0	.020
" (2).....	2.75	125	"	.034	45.0	.030
" (3).....	2.75	125	"	.058	46.5	.031
Fig. 14 (1).....	2.25	300	Brass	.115	15.0	.010
" (2).....	2.25	170	"	.066	45.0	.030
Fig. 15 (1).....	2.25	58.5	Brass	.018	51.0	.034

II. The E. M. F. of the battery in the branch A. An increase of the battery E. M. F., other things being equal, always increases the duration of the arc.

III. The speed at which the terminals of the circuit-breaker are separated. Increase in the speed at which the terminals of the circuit-breaker are separated hastens the destruction of the arc. Figs. 13, 6 and 7 illustrate this point.

IV. The metals of which the terminals are composed. We have seen in Figs. 6 and 7, that a break by copper terminals is of shorter duration than a break from brass. A break with zinc terminals does not seem to differ greatly in duration from a similar break with brass.

(*b*) The character of the arc formed varies, of necessity, with any condition that affects the duration of the arc. In particular, however, zinc terminals seem to produce a very irregular arc. In Fig. 8, the irregularities in the current curves are peculiar to zinc breaks. The curve for I_B with zinc terminals, not shown in this paper, possesses similar irregularities.

(*c*) The E. M. F.'s induced by the break, as indicated by the induced current flowing through B, vary also, of necessity, with any

condition that affects the duration of the spark. The maximum induced E. M. F. varies with :

(1) The current flowing at the instant of break. From Figs. 10 and 11, as tabulated in Table I., Fig. 17 is plotted, showing the variation of maximum induced E. M. F. with the current.

(2) The E. M. F. of the battery. The variation is shown

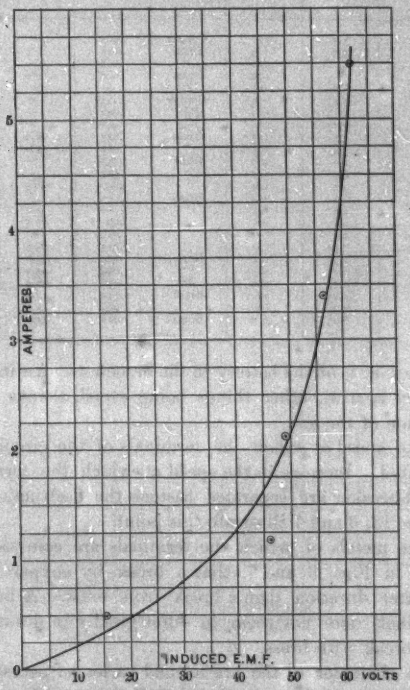

FIG. 17.

in Table I. An increase of E. M. F. prolongs the duration of the spark and prevents a high induced E. M. F.

(3) The speed of breaking. Owing to the vibrations of the needle, the height to which the curve actually rises is difficult to determine. There seems to be very little difference, however, between these curves in this respect. Other experiments, how-

ever, described below, show that the maximum induced E. M. F. increases with the speed of breaking.

The apparatus described above was constructed with the aid of Mr. W. J. Lester, and, with his help, experiments were made to determine the E. M. F. induced in the field of a motor when the current flowing through it is broken. The motor used was a Thomson-Houston, No. 3322, Class 30 R. 500 volts. The field coils in parallel had a resistance of 2.05 ohms and a self-induction

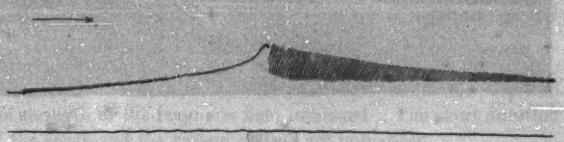

FIG. 18.

of .15 henry. The arrangement of apparatus was as before (Fig. 4), c being, now, the field of the motor disconnected from the armature, while the source of E. M. F. in A was 100-volt mains.

In order to hasten the destruction of the arc, in some of the experiments an electro-magnet was placed so that the arc formed in a magnetic field. Under such circumstances, the curves obtained were very irregular and the vibrations of the needle became so great that it was found necessary to drop the plate more slowly,

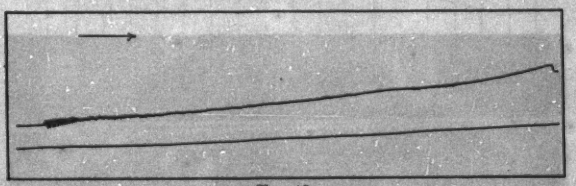

FIG. 19.

in order to get greater effect on the plate. By means of a pulley fixed at the top of the slide, over which passed a cord to which was attached the plate holder and a counter-weight, any desired speed could be obtained.

The electro-magnet, used to blow out the arcs, consisted of 100 turns of No. 18 B. and S. copper wire, wound on wrought-iron pole-pieces about 2.5 cms. in diameter, on which were mounted tapering pole-tips. This magnet had been previously calibrated

in the laboratory, but since it was inconvenient to place the terminals of the circuit-breaker directly between pole-tips, the strength of the magnetic field could only be estimated very approximately. During the experiments, the strength of the field varied probably from 1,000 to 3,000 lines per sq. cm.

FIG. 20.

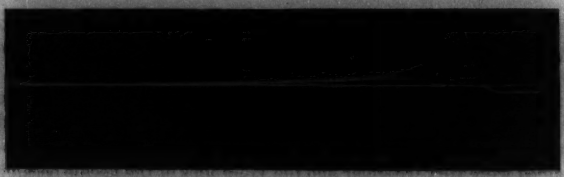

FIG. 21.

FIG. 22.

Fig. 18 is one of the curves obtained. An interesting point to be noticed is that the curve passes its maximum point before the spark ends, differing in this respect with the curves above. Other curves were obtained, showing this same feature. I_0 is 11 amperes, the duration of the spark .05 seconds, and the maximum induced E. M. F. 365 volts.

Fig. 19 shows a curve obtained when I_0 is 42 amperes. The spark lasts much longer. No marked disturbance can be detected on this curve to mark where this spark ends, but only a slight vibration after the drop from the highest point of the curve. The duration of the spark is probably .14 second, and the maximum induced E. M. F. 265 volts, which is less than in the preceding case when I_0 was only 11 amperes.

Fig. 20 shows the form of curve when the plate is dropped slowly and the arc blown out by a magnet. I_0 is 12 amperes, and the duration of the spark .03 second approximately. The maximum induced E. M. F. is 500 volts.

Fig. 21 is a similar curve obtained when I_0 is 11.5 amperes and the strength of the magnetic field increased. The short duration of the spark and the violent ending are noticeable.

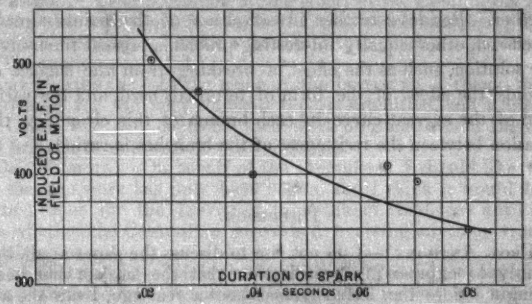

FIG. 23.

Fig. 22 illustrates a very irregular break. A number of curves were obtained of this form when the resistance in series with the voltmeter was 33,000 ohms. Further investigation is required to determine the cause.

In a thesis by W. J. Lester and the writer (Sibley College Library, Cornell University), descriptions and photographs of all the curves obtained may be found. Table II. shows data of some of the curves, while Fig. 23 is a curve, from the thesis, showing the variation of maximum induced E. M. F., with the duration of the spark, I_0 being constant and equal to 20 amperes.

TABLE II.

No.	I in Field. Amperes.	Duration Spark.	Induced E. M. F. Volts.
1	20.5	.08	430
2	21.2	.07	395
3	11	.05	365
4	20	.08	355
5	32	.08	290
6	42	.14	265
7	20	.02	475
8	20	.02	505
9	32	.03	530
10	32	.02	585
11	11.5	.04	370
12	12	.05	490
13	13	.05	295
14	13	.02	340
15	29	.02	710

The results presented in this paper must be accepted as illustrative of the method of experimentation adopted, and as outlining problems, which the writer hopes to be able to investigate further. Besides a further investigation of the points already discussed, other equally interesting problems present themselves for solution, such as the effect of breaking from the surface of liquids, the effect of the form of terminals used, and the variation of the current curve in each branch of this circuit, as the relation between the resistances of the branches is varied.

Discussion.

Prof. Anthony:—I do not rise to discuss the paper at all, but simply to express my gratification that the subject has been brought before the Institute. About a year ago, I saw the apparatus at Cornell University. It all depends on the extreme delicacy of the little magnet, having such an extremely high period of vibration of its own, that the vibration rate is entirely removed from the results that are obtained. In other words, it does not in any way affect the results that are obtained. Before I saw this apparatus, however, Prof. Brackett, of Princeton, had shown me a somewat similar arrangement of his own, which he had been at work upon without knowing anything about the work being done in the same direction at Cornell. I speak of this simply to call attention to a very interesting investigation which he was making, which I believe has also been carried out with this apparatus. By the use of two mirrors, one placed in a coil across an alternating circuit, and the other in a coil included in the alternating circuit, and throwing the reflected light to the same point when the mirrors were in equilibrium, he was able to obtain the relation between the alternating electromotive force

and the current of an ordinary alternating machine. He had a number of results which showed that very nicely under different conditions. One mirror, of course, would vibrate in phase with the current; the other in phase with the electromotive force.

MR. A. J. WURTS:—As I understand the speaker, the fluctuations with brass electrodes were quite marked. I should like to ask what the composition of the brass was?

DR. NICHOLS:—It was commercial brass. I do not know the composition. It was probably rolled brass. I should say it was a brass and not a bronze.

[At this point the President called Vice-President Steinmetz to the Chair.]

THE CHAIRMAN:—Gentlemen, after this interesting paper, I think a vote of thanks should be given to Mr. McKittrick and Dr. Nichols.

[On motion, a vote of thanks was tendered to the gentlemen named.]

MR. HOWELL:—I also think the INSTITUTE should make some expression of its appreciation of the labors of the Committee, in making the report on Standards of Light, which was presented to us this morning. I make a motion to that effect.

[The motion prevailed.]

THE CHAIRMAN:—In the name of the INSTITUTE, I thank the gentlemen for the very valuable reports submitted, and I hope the Committee will continue their work on Standards of Light, and bring it to as satisfactory a conclusion.

DR. NICHOLS:—On behalf of the Committee, I should like to say that the work has only been begun, and I think it would be quite proper for the INSTITUTE to withhold its thanks until it sees whether the Committee succeeds in evolving anything from its labors, or not.

THE CHAIRMAN:—While the work of the Committee has not been completed, and it has not been possible yet to make a definite recommendation of a standard of light, sufficiently valuable work has been done and embodied in the report under discussion, with regard to the features of the various proposed standards, the sources of error to be guarded against, and the relative value of the different proposed systems, so that I think the INSTITUTE is fully justified in agreeing upon a vote of thanks to the Committee.

MR. HOWELL:—We ought to thank the Committee, at least, for the expression of inaccuracy regarding our present standard. I read this week in a paper published at one of the leading technical schools of this country, by one of their graduates, who is a gas engineer, and the subject was Practical Photometry, or Commercial Photometry. It described the photometric apparatus used in gas works, and it concluded by saying that photometric observations were reliable within one per cent., which is very much in contrast with what Dr. Nichols told us this morning.

DIED.

SHRADER:—At Columbia, Mo., August 13th. Dr. William Shrader, Professor of Electrical Engineering, University of Missouri. Dr. Shrader was one of the leading scientists of the country. He had recently devoted much attention to Röntgen ray experiments. Dr. Shrader served as one of the judges in the Electrical Department of the World's Fair in 1893, and was elected an associate member of the INSTITUTE, September 20, 1893.

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